

# Analysis of an on-line superconducting cryofan motor for indirect cooling by LH<sub>2</sub>

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**Abstract.** This work relates to the study of an electrically powered cryofan for circulating close-loop cooling helium gas for superconducting applications with the following features:

- Absence of any seal that can leak the pumped fluid or provide a path for heat transfer and require maintenance and/or is prone to failures.
- The use of high temperature superconducting (HTS) stacks on the fan-rotor that, below critical temperature, can be magnetized contributing to the driving torque.

The absence of electrically connected equipment as well as the lack of any seal, makes this arrangement especially suitable for reliable cryogenic helium gas circulation. Because HTS stacks cannot provide magnetic flux above  $T_c$ , during the initial stages of operation, in the presented study we analyse torque that will be provided by the passive iron components of the machine (reluctance torque, due to the saliency of the rotor) and by auxiliary permanent magnets or alternatively magnetizing coils.

## 1. Introduction

The pumping of cryogenic fluids offers a stimulating environment for the commercial application of superconductors [1]. Up to certain limits, the task of cooling the motor can be left to the transferred fluid, liberating the machine of ancillary equipment that increases cost and reduces the expected time-to-failure of the equipment.

Thus, works on the matter have been proposed recently. For instance, in [2] an induction motor is designed for moving a liquid nitrogen circulator to cool down a high-temperature superconducting power transmission cable. The design procedure is carried out for a conventional, resistive, rotor cage, which was latter replaced by an HTS winding, this approach showed the characteristics that motors under this kind of applications must exhibit compared to larger (i.e. ship propulsion) ones: simplicity in the rotor and absence of connections of this element to external devices. This is especially critical in applications that involve liquid hydrogen, which can be used for cryogenic refrigeration, combustion, or in hybrid transfer lines application [3], where ignition sources in contact to the fluid must be avoided as far as possible.

Hereof, the authors propose further simplifying the structure of the machine's rotor by employing the newly developed superconducting stacks [4]. Stacks of superconducting tape layers can trap fields exceeding the performance of bulk superconductors due to their laminated structure [4, 5], in which the superconducting material is deposited on, among others, a metallic layer that provides mechanical stiffness, improves thermal conduction, and may add other important material characteristics that affect the operation characteristics of an electrical motor, such as an increase in magnetic permeability. Below  $T_c$ , the superconducting stacks perform the role of permanent magnets, supplying the magnetic flux density  $\mathbf{B}$  that interacts with the stator currents to produce torque. For sinusoidal quantities the average tangential stress in the airgap, which when acting on the rotor surface is responsible for the torque yielded of the machine, can be expressed as described by equation (1) [6]:

$$\sigma_{tan} = \frac{\hat{A} \hat{B} \cos \zeta}{2} \quad (1)$$

where  $\hat{A}$  is the peak value of the surface stator current,  $\hat{B}$  is the peak value of the magnetic flux density and  $\zeta$  is the angle – spatial phase shift – between both waves. Hence, a way of increasing the power density of a superconducting electrical motor is to attain values of  $\hat{B}$  higher than the ones supplied by permanent magnets based on rare-earth materials ( $\sim 1.3$  T), values that can be easily surpassed using superconducting stacks provided that the rest of the magnetic circuit is able to sustain that flux density (iron-cobalt commercial alloys will, for instance, saturate at 2.35 T).

Furthermore, electromagnetic losses in the motor's iron decrease the machine performance and even more dramatically affect its size, due to the square-cube law that relates the surface needed to release those losses to the environment with its volume. Divided in hysteretic, eddy current and excess losses, they can be calculated from their corresponding tabulated coefficients,  $k_h$ ,  $k_e$ ,  $k_{ex}$  and also  $\alpha(f)$  following expressions such as described by eq. 2 [7]:

$$\frac{h_{losses}}{m_{iron}} = k_h(f) f B^{\alpha(f)} + k_e f^2 B^2 + k_{ex} f^{1.5} B^{1.5} \quad (2)$$

where  $m$  represents mass,  $f$  accounts for the frequency and  $B$  for the root mean square value of the corresponding magnetic flux density harmonic,. In superconducting applications, the heat released by these effects should be minimized and the remaining transferred preferably away from the working fluid.

## 2. Proposed solution

The proposed solution consists of a homopolar inductor machine [1], which could be considered as two radial synchronous machines coupled by the same shaft, one having in the rotor the north poles and the subsequent one the south poles, (hence its name) presented schematically in Fig. 1. The magnetic circuit is closed between both halves by two iron sockets, one mounted in the rotor and other on the stator, flowing the magnetic flux axially through them. Enough clearance is left in the latter to install an axially centered coil endowed with the task of providing the field excitation. A rugged synchronous machine with no electric components in the rotor is thus obtained, which simplifies its operation and maintenance and allows higher rotational speeds. The main drawbacks of such a configuration stem from the difficulty in computing the 3D magnetic fields needed for its design (the magnetic flux moves radially between stator and rotor and axially between both halves of the machine) and its bulky construction, which yields a low power density. Nowadays conventional versions of this kind of machines are being considered for applications in flywheel storage systems, taking advantage of the inertia of its relatively large rotor.

What the authors propose in this work is keeping the advantages of this design whilst increasing its power density by applying the latest advances in superconductor materials with its intended use as a cryogenic fluid circulator. Superconducting stacks mounted on the rotor immersed in the cryogenic fluid provide a magnetic flux density for the operation of the motor as a permanent magnet machine under



coil. The stator winding is designed in a single layer, fixed between the stator iron and the insulating jacket, connected in four parallel paths. The characteristics of the machine are presented in Table 1:

**Table 1.** Geometric characteristics of the machine shown in Figure 1

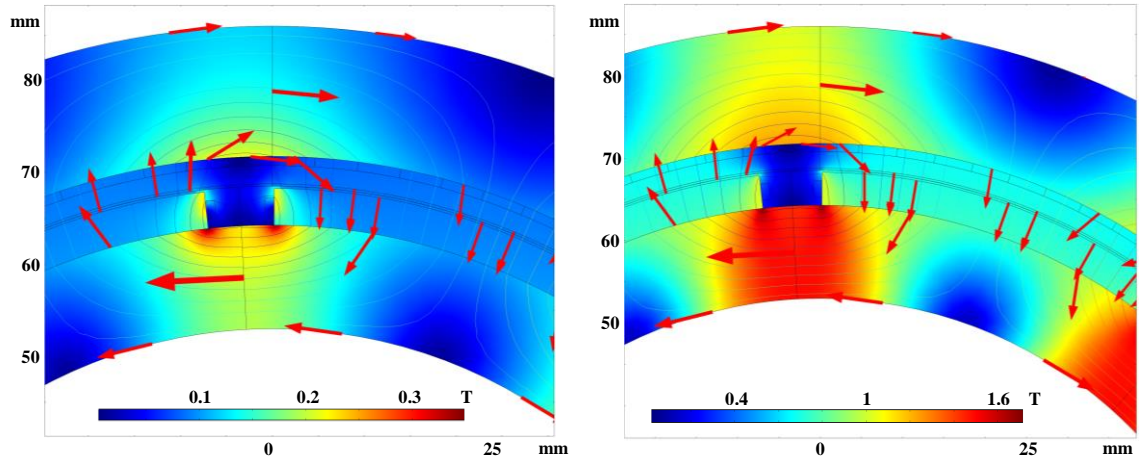
Number of phases	3
Number of pole pairs	4
Total number of stator turns	96
Number of parallel branches	4
Number of field coil turns	500
Inner diameter	53 mm
Rotor yoke width	11.3 mm
Stack height	4 mm
Airgap length	0.5 mm
Insulating jacket width	2 mm
Stator winding width	1 mm
Field coil dimensions	20 x 20 mm

Two finite element (FE) 2D models have been used to validate the initial analytical calculations of the 3D design represented in Figure 1. The first one describes a section of the machine in  $x$ - $y$  coordinates where the North and South pole stacks have been represented at the same  $z = 0$  level in order to compute stator currents and torque. The other is used to check the field coil current needed to magnetize the machine above  $T_c$ , assuming a permeability  $\mu_r$  for the stacks of 10, thus studying it in the perpendicular to the first  $z$ - $y$  plane with  $x = 0$ . The results summarizing the outcome of both approaches are shown in Table 2:

**Table 2.** Characteristics of operation

	Superconducting operation	Conventional operation
$B_{rem}$ (stacks)	1.33 T	0 T
Field current	0 A (DC)	1 A, 2 A (DC)
Stator current	10 A (rms)	10 A, 20 A (rms)
Back-EMF	2.98 V (square)	0.394 V – 0.779 V (square)
Torque	0.376 N·m	0.05 N·m – 0.2 N·m

According to the FE simulations, the machine can produce the required torque with a current of 2.5 A circulating for each branch of the stator windings during superconducting operation if the trapped flux is  $\sim 1.3$  T. Above  $T_c$ , the torque is reduced to 13.3% of the superconducting one maintaining the same stator current (10 A). However, if the currents in the stator winding and field coil are doubled (something especially feasible for the first of them since there the current density is low due to the diameter of the motor), the conventional yielded torque can reach 53.2 % of the superconducting one. Furthermore, the reduction of back-EMF facilitates this increase of current from the point of view of the variable speed drive that would control the motor. Fig. 2 presents frame captions (0.01s) of the time-stepping FE simulations performed showing low saturation of the magnetic circuit indicated by values in the colour-coded bars. A 3D model may be needed to confirm these values.



**Figure 2.** 2D  $xy$ -plane finite element analysis of the motor operating with the field coil energized (left) and with stacks magnetized (right) represented in both cases at the same  $z$  level. These figures show a 2D approximation to the radial effects in the machine for the area between the dotted lines in Fig. 1.

#### 4. Conclusions

This contribution presents a design of a superconducting machine applicable to a cryofan circulator, able to operate above  $T_c$  using stacks of HTS tape with a higher magnetic permeability than air. In conventional mode, a field coil winding mounted coaxially on the stator provides the required magnetic flux density, whose path is guided by the stacks. Below  $T_c$ , the flux trapped in them provides the excitation, with the field coil being used intermittently to top that flux following any eventual demagnetization. The machine does not require either any seal or there is also no leakage path for the fluid or any electric circuit in the rotor, being especially suitable to pump  $\text{LH}_2$ . The design is in its preliminary stage but in principle values of magnetic remanence of 2.35 T could be obtained, roughly doubling the ones currently used in permanent magnet motors. This work will be used to develop a fully functional efficient on-line cryofan for electric plane applications.

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